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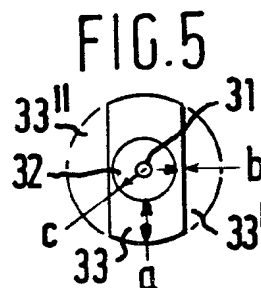Ramaswamy, Rogers Hall
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(54) **Optical waveguides having non-uniform outer jackets**

(57) Orthogonally polarised waves in an optical waveguide are decoupled by providing stress-induces birefringence greater than 5×10^{-5} in the waveguide. The birefringence is achieved by providing a jacket 33 which is of non uniform thickness which upon cooling exerts a sufficient strain upon the waveguide. A single polarised wave can be supported in such a guide without decoupling.

The optical fibre preform shown has a core 31, cladding 32 and outer jacket 33.

Optical fibre preforms having an inner core surrounded by a cladding and an outer jacket of non-uniform thickness at least partially surrounding the cladding are prepared.
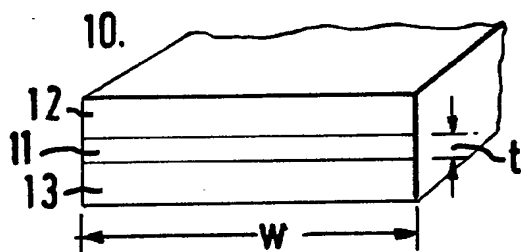

FIG.5

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FIG.1

10.

12
11
13

t

w

FIG.2

15 14
16
16

t_1
t_2
t_3

y

w_1 w_2 w_3

FIG.3

20.
21
22

FIG.4

30.
31
32
33

FIG.5

33^{II} 31
32 b
c 33^I
33 a

FIG.6

x
31
b^I y
32 c^I
33 a^I

FIG.7

40 41
40^{II} 40^I

FIG.8

40
41
40

FIG.9

51
50
52

FIG.10

60

0.278"

.099"

0.255"

FIG.11

60
63
64
65

FIG.12

60

65'

66

FIG.13

71

72

FIG.14

81

82

FIG.15

91

92
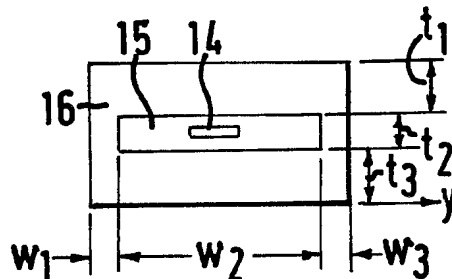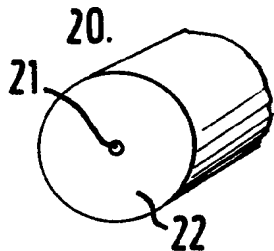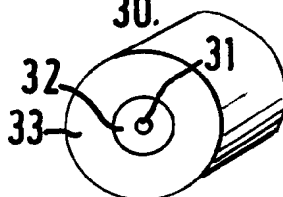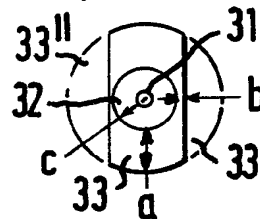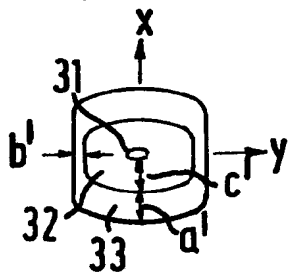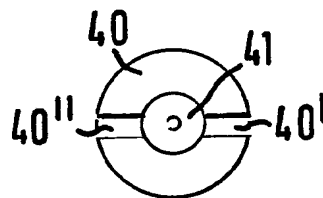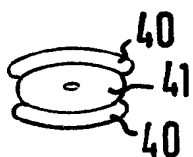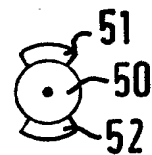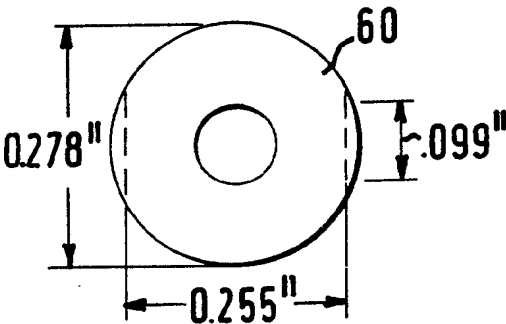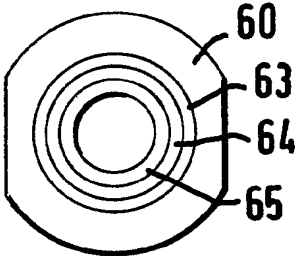
SPECIFICATION
Optical waveguides

This invention relates to optical waveguides
supportive of wave propagation with only one
5 direction of polarisation.
   Optical waveguides capable of transmitting
power with only one direction of polarisation are
desirable for use with integrated optical devices.
However, it is well known that geometric or
10 dielectric imperfections in conventional graded-
index fibers depolarise light after only a few
centimeters of propagation. While some slight
improvement in the polarisation performance of
these fibers is achieved by distorting the fiber core
15 symmetry as a means of decoupling the
differently polarised waves, an analysis, based on
an article by E. A. J. Marcatili entitled "Dielectric
Rectangular Waveguide and Directional Coupler
For Integrated Optics" published in the September
20 1969 issue of the Bell System Technical Journal,
pp.2071—2102, shows that simply changing the
core geometry does not appreciably alter the
difference in the propagation constants of the two
orthogonally-polarised fundamental modes.
25   An alternative approach to this problem is
disclosed in U.S. Patent 3,659,916 which
discloses a fundamental mode strip waveguide in
which a lossy material is placed along one surface
of the guiding strip to suppress one of the two
30 orthogonally polarised modes. Alternatively, a
higher refractive index material can be used
instead of a lossy material as a means of
destroying the waveguide's ability to guide one of
the modes. While these techniques serve to
35 suppress one of the two modes by absorption or
radiation, they do not preclude coupling between
the modes. As a result, there is a constant draining
of power from the preferred polarisation to the
undesired polarisation, and consequent loss. Thus,
40 single polarisation waveguides of the type
described tend to be unduly lossy.
   According to one aspect of the present
invention there is provided a single polarisation
optial waveguide at least partially surrounded by
45 and comprising an outer jacket, wherein the strain
birefringence of the waveguide is greater than 5 ×
10^{-5}, and wherein the jacket is of non uniform
thickness.
   According to another aspect of the present
50 invention there is provided a method of preparing
an optical fiber preform, comprising an inner core
region surrounded by a cladding and an outer
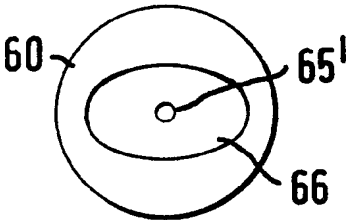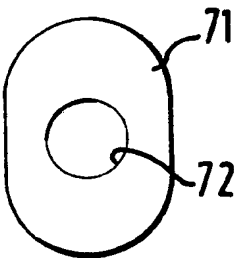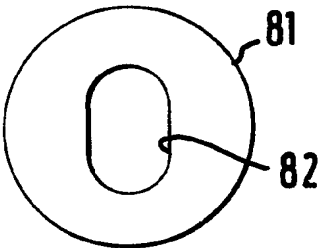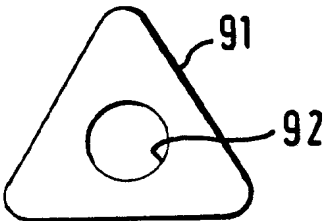jacket at least partially surrounding the cladding,
wherein the jacket is formed with portions that are
55 substantially thicker than other portions of the
jacket between the first mentioned portions.
   The present invention is based upon the
recognition that orthogonally polarised waves are
more efficiently decoupled in a waveguide that is
60 fabricated in a manner so as to deliberately
enhance stress-induced, or strain birefringence.
This behaviour is accomplished by introducing a
geometrical and material asymmetry in the
preform from which the optical fiber is drawn such

65 that the resulting stress induced or strain
birefringence Δn is advantageously greater than 5
× 10^{-5}. The resulting beat period, L, for such a
waveguide is less than 20mm at 1 μm wavelength
and less than 10mm at 0.5 μm, where L = $2\pi/\Delta\beta$,
70 and $\Delta\beta$ is the difference in propagation constants
for the two orthogonal directions of wave
polarisation of interest.
   Methods for fabricating fibers with Δn as large
as 40 × 10^{-5} are described. In this case L is 2.5
75 mm at 1 μm wavelength, and 1.25 mm at 0.5 μm.
   While stress-induced birefringence, of a
magnitude on the order of 10^{-7}, has been
measured in conveniently drawn optical fibers (see
"Birefringence in Dielectric Optical Waveguides,"
80 by F. P. Kapron et al., published in the IEEE Journal
of Quantum Electronics, Vol. QE-8, No. 2, February
1972, pp. 222—225), the size of the effect is
insufficient to reduce polarisation coupling to a
practically useful level. Furthermore, stress-
85 induced birefringence was not recognised as a
possible means for reducing such coupling.
   For a better understanding of the invention
reference is made to the accompanying drawings,
in which:
90   FIGS. 1 and 2 show two planar optical
waveguides;
   FIG. 3 shows a circular optical fiber preform
comprising an inner core surrounded by a
cladding;
95   FIG. 4 shows a three-layered, optical fiber
preform;
   FIG. 5 shows the preform of FIG. 4 after
diametrically opposite portions of the outer layer
have been removed;
100   FIG. 6 shows the cross-section of a fiber pulled
from the modified preform of FIG. 5.
   FIGS. 7 and 8 show, respectively, an alternate
means for modifying a three-layered preform to
enhance the strain-birefringence, and the cross-
105 section of a fiber pulled from such a preform; and
   FIG. 9 illustrates a method of modifying a two-
layered preform to produce stress-induced
birefringence in an optical fiber;
   FIG. 10 shows an end view of a substrate tube
110 used in the practice of an embodiment of the
invention;
   FIG. 11 shows an end view of a preform (before
collapse) fabricated according to an embodiment;
   FIG. 12 shows an end view of a fiber fabricated
115 according to a further embodiment; and
   FIGS. 13, 14 and 15 show end views of
alternative embodiment shapes of substrate tube.
   In the embodiments of the invention described
in Figs 1 to 9, the jackets are applied to the
120 cladding. In the embodiments described in Figs.
10 to 15, the jackets are prepared as tubes, and
the cladding and core are deposited in the tube
prior to drawing the tube to form the preform.
   Referring to the drawings, FIG. 1 shows a
125 planar waveguide 10 comprising an inner
dielectric member 11 and two outer dielectric
layers 12 and 13 which are in contact with the
major surfaces of member 11. In order to provide
wave guidance primarily within the inner dielectric

member 11, or core region of this waveguide, the refractive index of the outer layers is less than that of member 11.

Notwithstanding the fact that the width w of
5 the core is many times greater than its thickness t, such a waveguide is capable of propagating optical wave energy polarised along directions parallel to both transverse dimensions of the core region. In the absence of any extraneous coupling
10 mechanism, a beat length, L, can be defined within which energy is completely exchanged between the two orthogonally polarised waves, i.e., the energy reappears in the same polarisation after completely being transferred to the other
15 polarisation. For a single-mode fiber this length, L, is given as

$$L = 2\pi/\Delta\beta, \qquad (1)$$

where $\Delta\beta$ is the difference in the propagation constants of the two orthogonally polarised
20 waves. It is apparent that by increasing $\Delta\beta$, the beat length can be reduced. Since mechanical perturbations having spatial periods that are comparable to the beat length cause unwanted coupling from one polarisation to another, the
25 beat period is advantageously made smaller than the perturbation periods typically introduced by the fabrication process, or by physical bends and twists encountered in the use of the waveguide. For example, at a wavelength of 0.63 μm a
30 borosilicate, graded-index fiber with nominally circular geometry has an L greater than 10 cm. Mechanical perturbations of comparable length are not unusual. Accordingly, wave energy injected with one polarisation and propagating
35 along such a fiber tends to become cross-polarised. Prior art planar fibers tend to yield cross-polarised wave energy notwithstanding the fact that the aspect ratio of the waveguiding region can be much different than unity. The
40 polarisation coupling, however, is avoided in accordance with the present invention by means of stress-induced or strain birefringence in the waveguide which is such that $\Delta\beta$ is greatly increased. The term "stress-induced
45 birefringence" or "strain birefringence" as used herein refers to the difference in principal refractive indices produced by the creation of a difference in the mechanical stresses along mutually orthogonal transverse directions within
50 the waveguide region. Thus, for example, a birefringence can be induced in dielectric layer 11 if the thermal coefficient of expansion of layer 11 is different from that of the outer layers 12 and 13. When this is so, the width of member 11 will
55 want to be different from that of layers 12 and 13 as the fiber cools while being drawn. However, because the three layers are bonded together they will all assume the same width, thereby creating an internal strain within member 11 along the w
60 direction when the outer layers are sufficiently rigid. However, as no such strain is induced in the t direction, the result of this anisotropic strain is to create a relatively large difference in the

propagation constants for wave energy polarised
65 along these two directions by means of the photoelectric effect.

The magnitude of the difference in the refractive indices Δn for the two directions of
70 polarisation is proportional to the difference in the strains along these two directions, and is given by

$$\Delta n \approx (\alpha_o - \alpha_i) \Delta T \qquad (2)$$

where α_o and α_i are the coefficients of thermal expansion of the outer and inner layers,
75 respectively; and ΔT is the difference between the operating temperature and the temperature at which the glass layers stiffen.

In order to provide an alternative wave guidance structure, the slab structure of FIG. 1 can
80 be modified, as shown in FIG. 2, to comprise an inner core region 14, surrounded by an intermediate cladding 15 of lower refractive index, and an outer jacket 16. Such a preform structure can be readilfy fabricated by assembling separate
85 slabs of glass, or by successive deposition methods well known in the art. Alternate methods for approximating such a preform are described in the greater detail hereinbelow.

To achieve the desired large birefringence in
90 the waveguiding portion, comprising core 14 and classing 15, the difference between the thermal coefficients of expansion of the jacket material and the waveguide material is made large. In addition, the slab dimensions advantageously
95 satisfy the following inequalities:

$$(t_1 + t_3)\, c_1 >> t_2 c_2 \qquad (3)$$

and

$$(w_1 + w_3)c_1 << w_2\, c_2, \qquad (4)$$

where c_1 and c_2 are the elastic moduli of the jacket
100 and waveguide materials, respectively. Typically, c_1 and c_2 will be approximately the same so that the above inequalities are primarily geometrical. In some cases, as will be shown below w_1 and w_3 are zero.
105 The strain birefringence for the embodiment of FIG. 2 is

$$(S_y - S_x) = (\alpha_1 - \alpha_2)\Delta T \qquad (5)$$

where S_y and S_x are the strains induced along the y and x directions, respectively; and $\Delta T = T_a - T_b$,
110 where T_a is the operating ambient temperature, and T_b is approximately equal to the "softening temperature" of the material, and α_1 and α_2 are the thermal expansion coefficients of the jackets and waveguide regions, respectively. For
115 simplicity, α_1 and α_2 are assumed to be independent of temperature when making estimates.

The strain birefringence Δn is given by

$$\Delta n = \frac{n^3}{2} (p_{11} - p_{12})\, (\alpha_1 - \alpha_2)\Delta T, \qquad (6)$$

where n is the refractive index and p_{11} and p_{12} are the photoelastic constants of the waveguide material.

Typically, a preform will comprise a pure silica
5 jacket, and a cladding and core made of borosilicate, germanosilicate or phosphosilicate glasses, where the core and cladding are differentially doped to obtain the desired index difference. For illustrative purposes, the silica
10 values for p_{11} and p_{12} are used in the following examples.

EXAMPLE 1
For a 5 mole percent B_2O_3 - SiO_2 cladding, the calculated Δn is 1×10^{-4}, where $n \approx 1.5$, $(p_{11} -$
15 $p_{12}) \approx 0.15$, $(\alpha_1 - \alpha_2) \approx -5 \times 10^{-7}$ degrees C^{-1} at $\Delta T \approx -850$ degrees C.

EXAMPLE 2
For a 25 mole percent G_eO_2 - SiO_2 cladding, the calculated Δn is 4×10^{-4}, where $n \approx 1.5$ $(p_{11} - p_{12})$
20 ≈ 0.15, $(\alpha_1 - \alpha_2) = -1.6 \times 10^{-6}$ degress C^{-1} and ΔT ≈ -1000 degrees C.

EXAMPLE 3
For a 12 mole percent P_2O_5 - SiO_2 cladding, the calculated Δn is 4×10^{-4}, where $n \approx 1.5$,
25 $(p_{11} - p_{12}) \approx 0.15$, $(\alpha_1 - \alpha_2) = 1.4 \times 10^{-6}$ degrees C^{-1} and $\Delta T \approx -1200$ degrees C.

In each of the preceding examples, the core and cladding are assumed to have approximately the same thermal properties.
30 Having recognised the operative mechanism, the principles of the present invention can be applied to adapt conventional optical fibers as well. Typically, an optical fiber is drawn from a preform 20 of the type illustrated in FIG. 3
35 comprising an inner core region 21 surrounded by an outer cladding 22. Because of its circular symmetry, there tends to be very little stress-induced birefringence in a fiber drawn from such a preform. Accordingly, an asymmetry must be
40 deliberately introduced to enhance the strain birefringence. More specifically, consider as the starting preform a three-layered structure 30 of the type shown in FIG. 4, comprising an inner core region 31, surrounded by an intermediate cladding
45 layer 32, and an outer jacket layer 33. In an embodiment of the invention, diametrically opposite portions of the outer layer 33 are ground away, or otherwise removed, leaving the preform as shown in FIG. 5 comprising core 31, cladding
50 32, and a modified outer layer 33 from which portions 33' and 33" have been removed. When such a modified preform is drawn, surface tension alters its cross-section to that shown in FIG. 6 which, it will be noted, approximates the slab
55 configuration of FIG. 2. As in the embodiment of FIG. 2, the outer jacket layer 33 produces a strain within the fiber along the y-direction that is much greater than that produced along the x-direction. The ratio of the two strains is related to
60 the thicknesses a, b and c in the preform, and corresponding dimensions a', b' and c' in the resulting fiber.

While any asymmetry will produce a strain birefringence, it has been found that beat periods
65 of less than 5 mm are achieved when the ratio of cladding radius c to the original thickness a is less than one-half, that is

$$\frac{c}{a} < 0.5. \qquad (7)$$

and when the ratio of the reduced thickness b of
70 the outer layer to the original thickness a is equal to or less than one-tenth, that is

$$\frac{b}{a} < 0.1. \qquad (8)$$

Fig. 7 shows an alternate means of introducing an asymmetry in the outer layer of the preform. In
75 accordance with this method, diametrically opposed 40' and 40" are cut in the outer layer 40 surrounding the cladding 41. A fiber drawm from such a preform took on the form shown in FIG. 8.

In accordance with a third method of
80 fabrication, illustrated in FIG. 9, diametrically opposed, annular segments 51 and 52 are added to cladding layer 50.

Which of these techniques is employed will depend upon the nature of the starting preform.
85 Some, such as borosilicate doped preforms, are typically made with three layers. Hence, the methods illustrated in FIGS. 5 and 7 would be used. On the other hand, when starting with a two layered preform, the method of FIG. 9 can be used.
90 In FIG. 10, an end view of a quartz substrate tube 60 is shown. The outer diameter is 0.276 inches to 0.279 inches. The inner diameter is 0.099 inches. Flat surfaces were ground on the tube sides as shown, the distance between flat
95 surfaces being 0.255 inches. The substrate tube was then mounted in an apparatus of conventional type for depositing layers of chemicals on the inside of the substrate tube. (The apparatus is basically a converted lathe, in which the substrate
100 tube is mounted in the conventional feedstock position and a gas heater is mounted on the tool drive). The interior of this substrate had been cleaned with commercial glass cleaner and distilled water and dried with a flow of nitrogen
105 gas. After being placed in the apparatus, the tube was heated to 1025°C while a mixture of 250 cc/min oxygen and 750 cc/min Argon flowed through it.

An outer layer of cladding was deposited by
110 flowing 250 cc/min of oxygen, 50 cc/min of 3 percent silane in Argon mixture, 16 cc/min of 1 percent diborane in Argon and 750 cc/min of Argon at a temperature of 985°C for 4 hours and 12 minutes. An inner layer of cladding was
115 deposited by increasing the flow of diborane in Argon to 26cc/min for 48 minutes while the other parameters remained as before.

A core layer was deposited by flowing 250 cc/min of oxygen, 25 cc/min of 3 percent silane in

Argon and 750 cc/min of Argon at 1060°C for 27 minutes.

The preform thus constructed is illustrated in FIG. 11. Substrate 60 has in its interior outer cladding layer 63, inner cladding layer 64, and core layer 65. It was then collapsed in one pass to an outer diameter of .0186 inches and then drawn into a fiber by conventional means. The fiber was 0.0046 inches in outer diameter.

Details of the process used to form the cladding and core layers may be found in "A New Technique for the Preparation of Low-Loss and Graded-Index Optical Fibers." J. B. MacChesney, P. B. O'Conner and H. M. Presby, *Proceedings of the I.E.E.E., 62,* 1280 (1974) and "Low-Loss Optical Waveguides with Pure Fused SiO_2 Cores", G. W. Tasker and W. G. French, *Proceedings of the I.E.E.E., 62* 1281 (1974).

During the collapse of this preform, surface tension on the outer surface pulls the outermost surface into a circular cross section, shown in FIG. 12, in which substrate 60' exhibits a circular outer surface and a non-circular inner surface resulting from a deformation of the interior in response to the outer surface tension forces. Cladding 66 includes the material from both cladding layers 63 and 64. Its exact shape will, of course, vary with the detailed parameters of the preform. The ellipticity of cladding 66 has been exaggerated in FIG. 12 for the sake of clarity. In general, the cladding-substrate surface is definitely elliptical in cross section and the surface between core 65' and cladding 66 is circular in cross section or has a very slight degree of ellipiticity. In some cases, the ellipticity of the core can differ greatly from that of the cladding. This seems to depend on the relative melting points of the core and cladding glasses. For example, a pure silica core in a borosilicate cladding will solidify while the cladding is still liquid and come out almost round. A similar fiber with a pure germania core, a borosilicate cladding and a Pyrex (Registered Trade Mark) substrate tube has a flat, ribbon-like core. Presumably, the core ellipticity could be controlled by doping to modify its melting point.

A fiber made according to the method described above has maintained polarisation over a length of 100m. better than 100:1 (i.e., when a beam of polarised radiation was coupled into the fiber and the input end of the fiber was oriented so that the mimimum amount of power was emitted from the output end in a plane at a right angle with respect to the main beam, that minimum amount was less than 1% of the power of the main beam).

It is believed that the polarisation of transmitted radiation is preserved by a combination of asymmetric geometry and stress birefringence. In theory, both of these ccnditions will tend to preserve polarisation and which is dominant in any case will depend on the parameters of the particular fiber in question.

In the case of the fiber discussed above, the core is circular or only slightly elliptical and the region of greatest geometric asymmetry is the cladding-substrate interface, where the electromagnetic field is weak. Geometric factors are less important than stress induced birefringence. The strain birefringence is greater than 5×10^{-5} in the embodiments described in FIGS. 11 to 15.

The fiber is stressed because the substrate and core materials (essentially pure SiO_2) have a different melting point from the cladding, which is doped to alter its index of refraction. As the preform cools after it has been collapsed, the substrate cools first, establishing the elliptical cross section for the still-fluid (or soft) cladding. As the cladding cools and hardens, it is prevented by the substrate from shrinking and therefore caused to occupy a larger volume than it would if the substrate were not there, with the result that the fiber is stressed. Since the substrate is asymmetric, the stress is also asymmetric, giving rise to birefringence.

The relative magnitudes of geometric and stress effects will depend on the shape of the fiber, the relative melting points and thicknesses of the different layers and also the method of drawing the preform into a fiber. The degree to which a given fiber preserves polarisation will also be dependent on the polarisation-scrambling aspects of the fiber — impurities, bubbles and irregularities in the fiber dimensions, among other things, and the net result of these competing effects must be determined empirically in any particular case.

The method described above employs a grinding step to produce an asymmetric substrate. This method has the advantage of being easy to vary, but the production of a quantity of fiber would be facilitated by forming the substrate tubes with an initial noncircular cross section configuration. The noncircularity need not be in the form of flat surfaces on the outside of this substrate, of course, and many other suitable shapes will be apparent to those skilled in the art. For example, the exterior surface 71 of the substrate may be elliptical, and the interior 72 circular, in cross section as shown in FIG. 13. The exterior surface 91 may even be triangular as shown in FIG. 15 (with a circular interior 92). Alternatively, the exterior surface 81 may be circular and the interior surface 82 may be elliptical as shown in FIG. 14. In this last case, the mechanical deformation of the interior produced by surface tension on the outer surface is lost, but the stresses produced by differential thermal contraction will remain.

All these different configurations have in common a substrate tube the thickness of which is substantially nonuniform, and represents the most general description of a substrate tube that may be used in the embodiments shown in FIGS. 11 to 15.

The illustrative fiber described above included cladding layers having a melting point lower than the melting point of the substrate, so that the cladding layer was under tensile stress. It is also possible, of course, to employ combinations of

cladding and substrate so that the substrate solidifies last and compresses both the cladding and core.

The illustrative fiber was a "W" fiber having two cladding regions. The invention also applies to a fiber having a single cladding layer, either uniformly doped or with a radial refractive index gradient. Such a single-cladding layer fiber has been fabricated by a method that differs from that described above only in that the 1 percent diborane in Argon mixture was flowed at the rate of 20 cc/min.

The location of the stress may be controlled by varying the composition of the cladding layers.The layer with the lowest melting point will solidify last, and in the illustrated fiber the stress appears to be concentrated there. The stress, therefore, can be concentrated near the core or near the substrate, depending on the melting points of the several layers and their coefficients of thermal expansion. The net effect of the stress will also depend on the relative thicknesses at the core, cladding and substrate, of course.

CLAIMS

1. A single polarisation optical waveguide at least partially surrounded by and comprising an outer jacket, wherein the strain birefringence of the waveguide is greater than 5×10^{-5}, and wherein the jacket is of non uniform thickness.

2. A waveguide according to claim 1, wherein the ratio of the thickness of the jacket along one direction is equal to or less than 0.1 of the thickness of the jacket along another direction orthogonal to the said one direction.

3. A method of preparing an optical fiber preform, comprising an inner core region surrounded by a cladding and an outer jacket at least partially surrounding the cladding, wherein the jacket is formed with portions that are substantially thicker than other portions of the jacket between the first mentioned portions.

4. A method according to claim 3, wherein the ratio of the thickness of the jacket between the said other and the first portions is less than 0.1.

5. A method according to claim 3, wherein the jacket is formed on the cladding to a uniform thickness with two diametrically opposed longitudinally extending slots along the jacket.

6. A method according to claim 5, wherein the jacket is initially formed to a uniform thickness and the slots are then removed therefrom.

7. A method according to claim 5, wherein the jacket is formed by adding to the cladding two annular diametrically opposed sections.

8. A method according to claim 3, wherein the jacket is formed as a tube of predetermined shape, cladding material is deposited on the interior of the tube by vapour deposition, a core layer is deposited on the interior of the cladding by vapour deposition, and the tube is collapsed by a heating process to form the preform.

9. A method according to claim 8, wherein one of the outer and inner surfaces of the jacket is non circular.

10. A method according to claim 9, wherein non-circularity of the outer surface of the tube is formed by shaping.

11. A method according to claim 8, 9 or 10, wherein the melting point of the cladding is lower than that of the jacket, whereby the stresses are induced upon cooling of the preform.

12. A method of preparing an optical fiber preform, substantially as hereinbefore described with reference to FIG. 2, or any one of FIGS. 5 to 9 or FIGS. 11 to 15 of the accompanying drawings.

13. An optical fiber preform prepared by the method according to any one of claims 3 to 12.